RSC
Applied Polymers

ROYAL SOCIETY OF CHEMISTRY

REVIEW

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Cite this: *RSC Appl. Polym.*, 2025, **3**, 767

Multifunctional soft actuator hybrids: a review

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Received 24th January 2025,
Accepted 30th April 2025

DOI: 10.1039/d5lp00022j

rsc.li/rscapplpolym

Stimuli material-based soft actuators is an ever-growing field, offering innovative solutions to the complex challenges of the modern world. Evolving from traditional single stimuli-responsive materials, multifunctional soft actuator hybrids have overcome previous limitations, exhibiting new potential in numerous applications and fields. This review provides initial insights into the recent developments and system integrations of stimuli-responsive polymeric soft actuators from the aspects of material development, mechanism design, and specific applications. It is elucidated that multifunctional soft actuators have versatile activation and can successfully demonstrate unrestricted movements, self-sensing, self-healing, electrochromism, and enhanced mechanical properties. Notably, from rehabilitation and surgical tools in the medical field to improvements in disaster rescue efforts, soft actuators are universally utilized and will be continuously expanding their applicability as research develops.

1. Introduction

The field of soft actuators is growing rapidly as it poses a unique solution to bulky mechanical actuators, and it has immense possibilities in mitigating limited design space obstacles and in biomimicry and medical devices.[1–4] The key advantages of compliancy, flexibility, and conformability of soft actuators stem from their innate "soft" aspect, often arising from their polymeric matrix.[5] The complex and continuous movements achieved by soft actuators further complement their utilization in irregular manipulation, delicate touches, and unrestricted maneuvers. This combination of advantages enables the design and development of new systems and inspires the re-thinking and re-evaluating of existing (mechanical actuators) and new operations.[6–8] The ongoing research on soft actuators is focused on many aspects, including the development and formulation of novel

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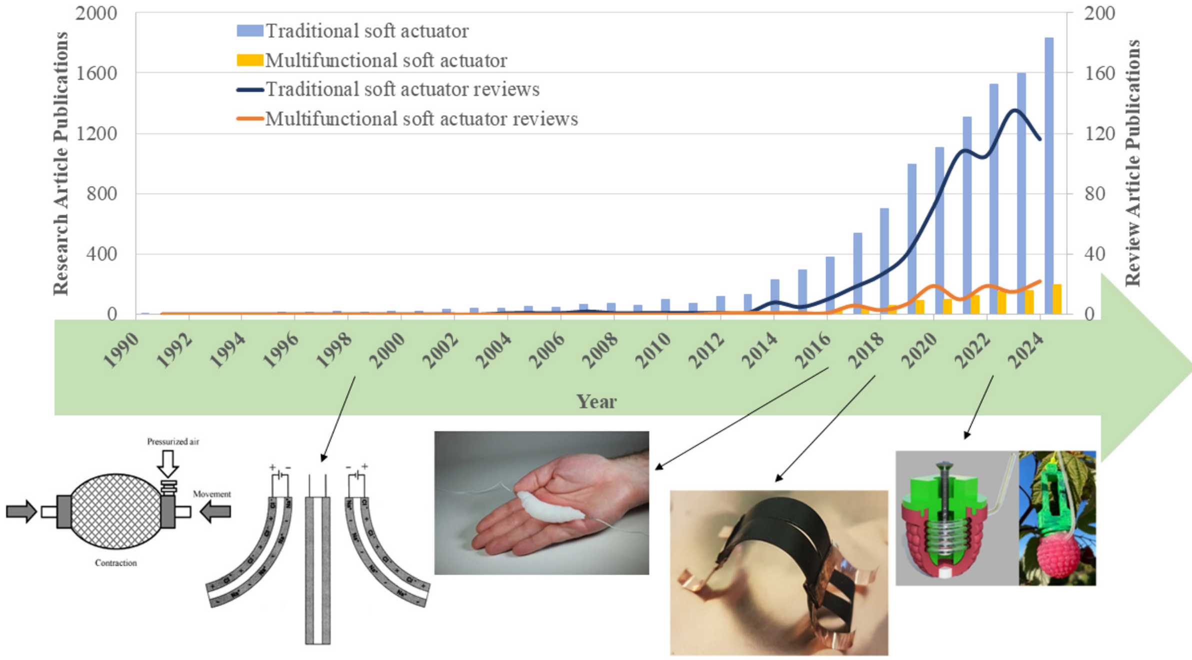

Fig. 1 Trends in articles and review papers on traditional soft actuators and multifunctional soft actuators. A few key devices during this timeline are highlighted, from left to right: graphic of McKibben artificial muscle first published in 1961.[59] Reproduced from ref. 59 with permission from Elsevier, Copyright 2025. Initial use of a carbon nanotube for bi-directional bending, published in 1999.[60] Reproduced from ref. 60 with permission from The American Association for the Advancement of Science, Copyright 2025. Electrically activated soft artificial muscle, published in 2017.[7] Soft crawling robot, which is bio-inspired from a worm locomotion and powered by electrothermal stimuli, published in 2019.[61] Grippers for raspberry harvesters, with 80% success rate and aiding the agriculture sector.[62] The data were obtained from the Web of Science using the keywords "soft", "robot", "actuator" for traditional soft actuators and additional keywords of "multi" and "function" for multifunctional soft actuators. The data projection matches the trend found in Google Trends.

soft materials, computational modelling for environment interaction, and physical intelligence and logic system integration.[9–15] While all facets of research promote soft actuators for real-world applications, material development and quality performance are the focuses of this review, laying down a stable basis for further innovations.[16–20]

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The functionality of traditional soft actuators is attained by utilizing stimuli-responsive materials (also known as active or smart materials).[21–26] Stimuli-responsive material-based soft actuators have the ability to react to external stimuli (electrical, thermal, and pneumatic) and exhibit a physical change as a response (geometrical and chromatic).[27,28] The field of soft actuators slowly emerged with the development of the McKibben artificial muscle in 1961, a pneumatic stimulus-activated actuator to assist polio patients.[29] In the next 50 years, the concept of soft and flexible actuators was occasionally explored, from piezoelectric polymer bimorph actuators[30] in 1983 to the electrical stimuli-driven locomotion of hydrogels[31] in 1992 and even the onset of bio-inspired soft fingers[32] in 1993. Each research highlighted the flexibility and diverse movement of the devices but no official designation was established for this field. Then, in 2008, the term "soft robotics" appeared,[5] and this trend picked up significantly in 2012, as can be seen from the number of publications (Fig. 1).

The most common soft actuator uses the input of compressed air to a tethered soft pneumatic actuator for the manipulation of delicate and small objects.[33] To enable the operation of devices without using a tethered power source, untethered soft actuators have been widely explored.[34] Popular untethered soft actuators include the use of thermal stimuli for two-way deformation of shape-memory polymers,[35] employing humidity changes for the shape morphing of hydrogels,[36–38] and the application of uniform magnetic fields, resulting in multiple forms of deformation such as bending, gripping, and rolling.[39–41] With tremendous interest, a simple flexible actuation device evolved into rehabilitation exosuits,[42] fully soft biomimicking "octobot",[43] and even integration into the agriculture sector[44] and artificial intelligence.[45] However, the challenges with soft actuators prevent their evolution into application-ready prototypes. These include their lack of mechanical properties, inability to survive in certain environments, high hysteresis, and limited generation of motion and force.[46] Some of these disadvantages are strongly related to their stimuli system, such as predetermined actuation motion and high-power consumption.[47–49]

Moreover, to truly utilize soft actuators in real-world operations, we must recognize the use of actuators not on their own, but as part of a vast system consisting of numerous integrated components to achieve a final functionality. Therefore, another challenge arises, where the post integration of multiple components into a single system results in design complexity, an increase in size and shape, and several exposed failure locations.[50] Currently, many traditional soft actuators in the literature target a single functionality/application through a single activation stimulus, limiting their practicality.[46,49,51–56] Driven by the complexity of current systems, aspiration to enhance their present performances and future application potential,[49] research into multifunctional soft actuators has steadily been growing since 2018,[54–57] such as a self-powered bio-inspired soft robot to freely swim in the sea.[58] However, despite the recent growth in multifunctional soft actuators, adequate review papers are lacking due to their novelty.

Multifunctionality is often defined as a material/composite that can perform more than one structural (mechanical property, such as stiffness and fatigue) and/or non-structural functions (actuation, sensing, and energy harvesting).[50,63] Multifunctional materials possess low weight, small size, and simplicity in design, resulting in enhanced durability, system-level efficiency, and decreased failure probability. In many studies, multifunctionality can also be achieved by combining different stimuli-responsive materials into a single system for the creation of soft actuator hybrids, as shown in Fig. 2.

In this context, we define the term "hybrid" as applicable at multiple levels. At the material level, hybrids refer to the integration of two or more stimuli-responsive materials, such as combining electroactive and magneto-responsive components, within a single composite or matrix to enable multi-modal responsiveness or enhanced functionality. At the system level, they encompass the incorporation of different functional components, such as sensing and self-healing ability, into a unified actuator architecture, where these elements are compositionally or structurally unified rather than simply attached externally. This distinction emphasizes that soft actuator hybrids are applicable through both material integration to engineer intrinsic multifunctionality and system-level design to achieve synergistic performances.

In these cases, the hybrid design responds to more than one external stimulus, possessing the robustness lacking by traditional single-stimuli-responsive materials.[50] Additionally, hybrid designs can perform more than an actuation function, such as additional non-structural sensing, energy storage, and/

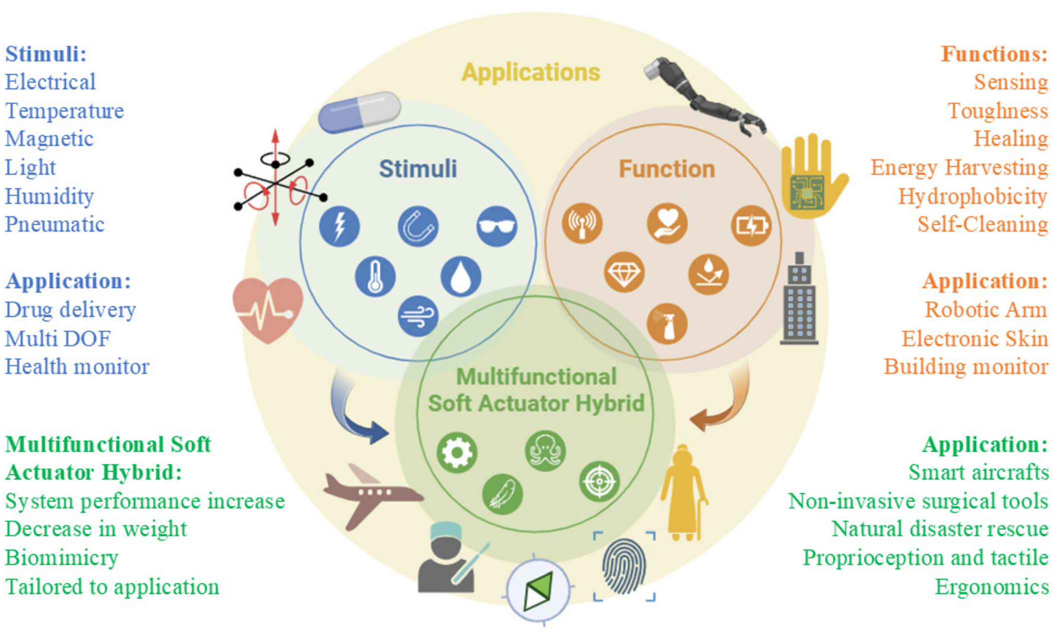

Fig. 2 Relationship between stimuli (blue), functions (orange), and their integration in multifunctional soft actuator hybrids (green), with their respective applications.

or healing abilities. These multifunctional soft actuators can be better tailored to specific applications because of their optimization through various material combinations to achieve the desired abilities.[50,64–69] Soft pneumatic actuators (SPA), for example, are prone to leaks due to the immense pneumatic pressure input required for actuation. Pena-Francesch *et al.* overcame this major problem by fabricating an SPA with self-healing properties. The rupture from excessive pneumatic pressure activates the self-healing properties in the composite, closing the ruptured area for continued actuation use and promoting a longer operational SPA.[65] By pushing this concept of multifunctionality, soft actuators are becoming self-sustainable, not requiring a constant input of control or maintenance but able to perform tasks autonomously due to their integrated additional functionalities such as sensing feedback loop, healing, and/or energy storage.[70]

This review focuses on polymeric soft actuators and their multifunctional hybrids, where each concept will be introduced and later reinforced in real-life application demonstrations. To achieve multifunctional soft actuators, various stimuli soft actuators are presented for in-depth understanding of their capability mechanisms. This review highlights the use of common stimuli-materials owing to the research into their operational mechanism, leading to less complicated multiple system integration. Firstly, the popular traditional stimuli soft actuators (piezoelectric, dielectric, magnetic, electrothermal, pneumatic, hydrogel, and photothermal) will be explored, and then prominent multifunctional soft actuator hybrids with additional functionalities (multiple external stimuli response, sensing, healing, structural, energy, and more). It is important to note that the addition of a separate device attachment to a material will not be considered in this review. For example, attaching a separate commercial sensor to a soft pneumatic actuator will not be discussed given that this review focuses on the modification and integration of materials.

2. Traditional stimuli-responsive soft actuators

Traditional stimuli-responsive polymeric soft actuators are defined by their ability to actuate to a stimulus.[21,71,72] The common stimuli-responsive systems for soft actuation are discussed in this section, including piezoelectric, dielectric, electrothermal, magnetic, pneumatic, photothermal, and hydrogel-based soft actuators (Fig. 3). Table 1 compares the qualitative characteristics of the traditional stimuli-responsive soft actuators discussed in Section 2 of this review.

2.1. Piezoelectric soft actuator

Piezoelectric polymer soft actuators are lightweight, conformable, and have fast response from their electrical stimuli.[79] Actuation through electrical activation is advantageous due to the ease of input power control and its universally accessible power source and fast response. Piezoelectric soft actuators exhibit spontaneous electric polarization and can undergo a converse piezoelectric effect, where an applied voltage results in expansion or contraction of the material depending on its polarity direction. Owing to this effect, piezoelectric polymers show great potential for many practical applications ranging from the automotive to medical to military fields.[80] Polyvinylidene fluoride (PVDF) is one of the most well-known piezoelectric polymers, which is inexpensive, environmentally friendly, and conformable. As a semi-crystalline polymer, PVDF has five distinct polymorphs (α, β, γ, δ, and ε). Among them, the stable non-polar α phase and electroactive β and γ crystal phases are the most researched. The β phase has the highest dipole moment (8×10^{-30} cm) per unit cell, and thereby the best piezoelectric property.[81,82] Therefore, the promotion of the piezoelectric property of PVDF through an increase in both its degree of crystallinity and electroactive phases, especially β crystal phases, is desirable to enhance its use as an actuator.[83]

PVDF actuators are ideal for micro actuation with accurate control, such as optical microscopes, cameras, and other instruments requiring high resolution.[84,85] To enhance its piezoelectric property by increasing its dipole moment, the addition of nanofillers such as carbon nanotubes (CNT),[86] magnetic cobalt ferrite ($CoFe_2O_4$) and nickel(II) hydroxide ($Ni(OH)_2$) nanofillers,[81,87,88] and various processing methods such as electrospinning[89,90] have been implemented. The electrostrictive strain of a PVDF composite was observed to double to 2.1% at 54 MV m^{-1} when 0.35 vol% of multi-walled CNTs (MWCNTs) was added.[91] Lee *et al.* embedded boron nitride nanotubes (BNNT), structural analogues of CNTs, in PVDF with post-processing and achieved 2.9 μm (V $mm^{-1})^{-1}$ deflection per electric field.[92] Ahn *et al.*[93] stretched already electrospun 1 wt% MWCNT/PVDF by 200% and achieved 1 μm of actuation with an electric field of 2 kV mm^{-1}. Electrospinning method produced a coaxially aligned MWCNT in a PVDF matrix. Even at a low nanofiller loading of 0.06 wt%, this nanocomposite actuator exhibited a high β phase crystal content of 94% and actuation under an electric field of 4 V $μm^{-1}$.[94] Additive manufacturing of PVDF has been proved to be a reliable processing method, where inkjet-printed P(VDF-TrFE) actuators could operate at a low voltage of 50 V.[95]

Piezoelectric actuators for biomimicking have been demonstrated by alternating the positive/negative voltage, which resulted in 0.4 mm extension/contraction in PVDF, allowing the robot to "crawl" forwards from this continuous motion.[73] Demonstrating biomimicry, a fast, flappable soft piezoelectric robot (BFFSPR) was fabricated with a 12 μm PVDF film as the active layer and copper film as the passive layer. This combination was assembled into a double spiral shape to mimic the "front and back legs" of animals. The double layer and the structure design of the BFFSPR allowed fast speeds of 42.8 body lengths per second and demonstrated a turning angle of 180°.[96]

2.2. Dielectric soft actuators

Dielectric elastomer actuators (DEAs) have a fast response time (<1 ms) and generate large forces (MPa) and large strain

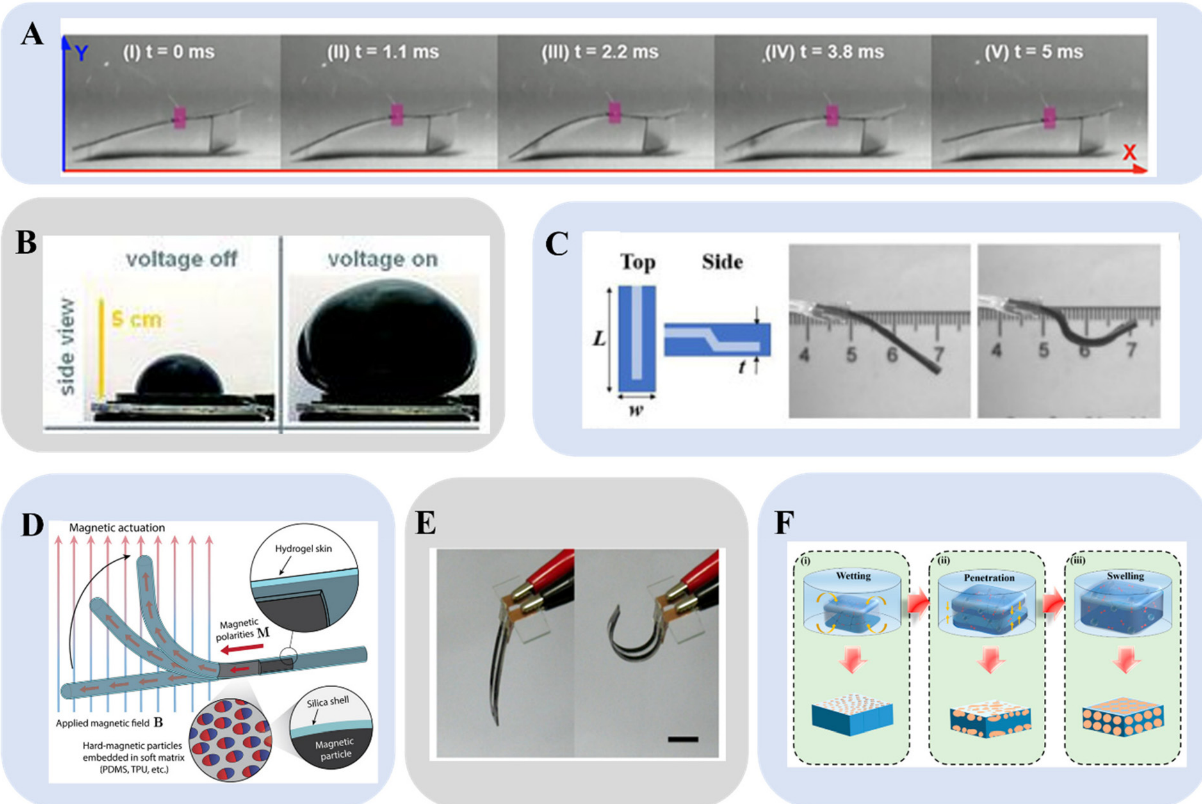

Fig. 3 (A) Curved piezoelectric soft actuator moving with fast locomotion owing to its curved unimorph structure with high amplitude vibration. Its fast movements are in the millisecond scale, moving at a speed of 20 body lengths per second.[73] Reproduced from ref. 73 with permission from The American Association for the Advancement of Science, Copyright 2025. (B) Dielectric soft actuator demonstrating a high voltage-triggered area expansion of 1692%. This is achieved by applying pressure to a critical point of instability, then applying voltage, which "snaps" expansion in the device.[74] Reproduced from ref. 74 with permission from the Royal Society of Chemistry, Copyright 2025. (C) Pneumatic soft actuator with shape engineering of interior air channel causing asymmetry at different locations (schematic on the left). This results in localized bending and achievement of an "S"-shaped deformation.[75] Reproduced from ref. 75 with permission from Elsevier, Copyright 2025. (D) Illustration of hydrogel/silica magnetic soft actuator with unidirectional polarized magnetic domain formed during fabrication. This leads to superior magnetic actuation when activated.[76] Reproduced from ref. 76 with permission from The American Association for the Advancement of Science, Copyright 2025. (E) Carbon nanotube in silicone elastomer polydimethylsiloxane (CNT/PDMS) electrothermal biomorph soft actuator with a thickness of 400 μm. The large difference in the coefficient of thermal expansion in the two materials leads to sizeable bending (220°) under an applied current.[77] Reproduced and adapted from ref. 77 with permission from IOP Publishing, Copyright 2025. (F) Hydrogel swelling mechanism, with the material soaked in seawater. With time, the water will penetrate through the pores of the hydrogel, and the material will swell, increasing in volume, until it reaches swelling equilibrium.[78]

(>100%) but require large electric fields (scale of kV mm^{-1}) for actuation.[97] Upon the application of an electric field, electrostatic pressure is created due to the Coulomb forces between the electrodes, denoted as Maxwell stress, causing DEAs to deform. As highly flexible elastomers, DEAs have a finite volume, and therefore are innately incompressible. To compensate for a deformation in one axis, such as a decrease in thickness, the other dimensions increase, keeping the volume constant, which results in an actuating motion.[98,99] Due to their high force output and fast reaction time, DEAs have been extensively researched for use as artificial muscles.[100] Thus, owing to the popularity of DEAs, many insightful review articles on DEAs and electrically driven soft actuators have been published, delving thoroughly into the materials, electrodes, and 2D/3D deformation of various DEAs for a wide range of applications.[101,102] However, DEAs have certain drawbacks, including the need for a high applied voltage (scale of kV), high energy consumption for operation, and the low electric breakdown of materials, which still need to be resolved.[103]

Kim *et al.*[104] used a DEA with localized graphene electrodes to obtain actuation at the center of a film. This DEA (100 μm thickness) performed the large displacement of 1050 μm at an applied voltage of 3 kV and 0.5 Hz. To achieve greater actuation in the center, Hajiesmaili *et al.*[105] used carbon nanotube-based electrodes with a meso-architecture. The circular DEA with dimensions of 80 μm by 11 mm produced 3.5 mm of deflection under 3.5 kV. Direction-dependent properties were exhibited by fiber-reinforced DEAs, where the fibers induced out-of-plane displacement in the pre-stretched DEA surrounding it. It was observed through simulation and experiments that with 4 fibers, the maximum out-of-plane displacement of 0.5 mm was achieved under 8 kV and a blocking force of 0.18

Table 1 Qualitative comparison of traditional stimuli-responsive soft actuators

	Actuation mechanism	Actuation scale	Response time	Blocking force	Advantages	Challenges	Applications
Piezoelectric soft actuator	Voltage-induced inverse piezoelectric effect	μm	Fast	Low	Fast response time, high accuracy	Small actuation strain, low blocking force	Micro positioning system, active vibration dampers
Dielectric soft actuator	Electric field-induced Maxwell stress	mm	Fast	Medium	High strain, fast response time	High voltage, prone to dielectric breakdown	Artificial muscle, tunable lenses
Electrothermal soft actuator	Temperature-induced thermal expansion	μm to mm	Slow	Medium	Ease of fabrication	Slow recovery, low power efficiency	Reconfigurable surfaces, shape-programmed robots
Magnetic soft actuator	Magnetic field-induced magnetic force/torque	mm	Fast	Medium	Untethered system, high accuracy, large deformation	High magnetic field at close range	Surgical tools, micro-robots
Pneumatic soft actuator	Compressed air-induced pressurized mechanical motion	mm	Fast	High	Large deformation, high force	Prone to ruptures, tethered and bulky	Prosthetics, rehabilitation tools such as exosuits
Photothermal soft actuator	Light conversion to heat causing motion	μm	Medium	Low	Untethered system	Specific light wavelength and intensity, low strain	Smart textiles, targeted drug delivery
Hydrogel-based soft actuator	Movement of ions causing swelling	mm	Slow	Medium	Large deformation, use in wet environment	Slow response time, complicated fabrication	Drug delivery system, tissue-engineering scaffolds

N.[106] A DEA with bi-stability could switch from one equilibrium state to another, allowing much faster DEA actuation with the low energy consumption of 0.14 J per grip due to no requirement of a continuous voltage to hold onto an object.[107] To enhance the energy density of DEAs, optimal electrodes to sufficiently charge them were explored. It was found that low-density, ultrathin CNT electrodes could apply electric fields as high as 100 V μm^{-1} without dielectric breakdown, with the DEA achieving an energy density of 19.8 J kg^{-1}.[108] A fully inkjet-printed dielectric elastomer was fabricated with a polydimethylsiloxane (PDMS) active layer between electrodes, demonstrating a 36 μm tip displacement under 1 kV.[109] A DEA was also used as a tunable optical device. The voltage-induced strain of the dielectric elastomer of up to 12 kV changed the focal length by 50% within 3.6 ms, focusing blurry images to clear objects.[110]

2.3. Electrothermal soft actuators

Although powered by an electric source, electrothermal actuators (ETAs) utilize the heat produced from voltage to obtain actuation. Joule heating drives the thermal expansion of ETAs as the kinetic energy of individual molecules increases and vibrates more at higher temperatures, leading to large separations between molecules, and subsequently an observable volumetric expansion.[111] Polymeric ETA materials require a low voltage, perform without electrolyte, and can produce large displacement and forces. One disadvantage is the eventual thermal stimuli, where the deformation back to its original state is governed by the slow rate of cooling, reducing the actuation time and low frequency.[18,112] ETAs are commonly fabricated as a bilayer system, with a conductive layer to initiate Joule heating and a flexible layer with a high coefficient of thermal expansion (CTE). With the mismatch of CTE between the layers allowing one layer to expand more than the other, bending will occur.[113] Compared to other thermal-stimuli responsive soft actuators, ETAs are not limited by a transition temperature, have reversible deformation, and more diverse material selection.[114]

Chen *et al.*[115] demonstrated that ultra-aligned CNT sheets significantly reduced the voltage required for ETA actuation. The actuation behavior to fiber orientation was also observed, where upon the application of electrical current in the direction of the fiber, less heat and actuation motion is generated because of the lower resistance.[116] Utilizing silver nanowires, a large bending of 720° at 4.5 V at a heating rate of 18 °C s^{-1} was achieved.[117] This bimorph ETA was demonstrated as a crawling robot and successfully manipulated delicate objects. Alternatively, a graphene oxide/silver nanowire conductive layer allowed a low power density input of 0.8 W cm^{-2} and was demonstrated with a bionic hand.[118] PDMS coated with a novel carbon nanotube (CNT) sponge, which was a CNT film layer with micro air voids created by the immersion of a CNT film into hydrogen peroxide. The use of the CNT sponge exhibited a high temperature and electrothermal conversion efficiency at a low voltage input, expanding up to 1.14 cm or an increase in volume of 70% at an applied voltage of 6 V in 24 s.[119] Zeng *et al.*[120] created a double layer PDMS/(PDMS/MWCNT) film, where the differing coefficient of thermal expansion (CTE) of the material layers resulted in buckling of the film and enhanced actuation. This ETA (0.37 × 10 × 48 mm^3) achieved a bending displacement of 28 mm under 7 V, and could lift 1538 mg, which correlated to 4.2 times its weight. Ye *et al.* fabricated an all polymer-based ETA using a combination of conductive and dielectric polymers. The CTE mismatch of the layers and the high conductivity of the conductive polymers polyaniline (PANI) and poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) allowed the all-polymer ETA to undergo deformation under electrically activated thermal stimuli. The ETA could reach 70 °C and curvature of 1 cm^{-1}.[121]

Nam *et al.* utilized filtration methods to fabricate uniform CNT buckypaper in a tri-layer with silicone elastomer, resulting in a 22% increase in displacement compared to the bilayer.[114] Sun *et al.* programmed an ETA into the desired configuration by applying the stress relaxation mechanism, resulting in active bending over 540° and demonstrated with a crawling inchworm-motion robot.[122] Also inspired by the caterpillar, Wu *et al.* fabricated a bidirectional crawling robot utilizing programmable silver nanowires distributed in a liquid crystal elastomer biomorph actuator device. Using heating patterns, controlled curvature was achieved for forward and reverse locomotion.[123] Additive manufacturing methods, such as screen printing and fused deposition modelling, can be used to fabricate ETAs and other thermally responsive soft actuators, which can heighten this field to industry level mass-production.[124]

2.4. Magnetic soft actuator

Soft actuators triggered by magnetic field stimulus are a non-contact and non-invasive approach. Under a magnetic field, magnetic soft actuators exhibit large and continued actuation with a fast response, precise control, and great flexibility.[76] These actuators are often constructed by embedding magnetic particles in low impedance materials.[49] It is common to utilize a uniform magnetic field to employ directional magnetization during the fabrication process to increase actuation in a particular direction. Alternatively, a non-uniform magnetization profile can be used to vary the orientation of the embedded magnetic particles and create localized actuation points. This increases the complexity of the resulting actuation shapes and motions.[125] Magnetic particles can be either micro/nano sized and are classified as hard/soft magnets. Hard magnetic fillers, such as neodymium (NdFeB), maintain their magnetization without an applied magnetic field, and therefore have higher saturation magnetization.[126,127] Soft magnetic fillers, such as iron oxide, lose their magnetization once the magnetic field is removed but can be easily re-magnetized.[126] Although many studies utilize NdFeB, it has a low operating temperature of 80 °C, where above this temperature, NdFeB loses all its magnetic properties and is disadvantageous in applications involving harsh conditions.[127] Soft magnetic filler iron oxide nanoparticles are extensively utilized in magnetic soft actuators due to their high magnetic saturation (84–92 emu g^{-1}), low toxicity, high magnetic stability, large surface area, and magnetothermal effect upon the application of an alternating magnetic field.[128,129] Furthermore, their low coercivity allows a magnetic device to truly be at rest by exhibiting low magnetic property in the absence of an applied magnetic field, which is beneficial for application where a constant magnetic field can be a disturbance to other nearby devices.

Paknahad *et al.* fabricated 116 µm-thick 5 wt% iron(II,III) oxide (Fe_3O_4)/PDMS and observed 33 µm actuation under 6.8 mT.[130] Wang *et al.*[131] observed the reprogram ability of magnetic soft actuators by applying a high magnetic field on multiphase polymer networks. Upon applying 11.2 kA m^{-1}, 50% programmed strain was achieved, which was sustained for 100 cycles. Reprogrammable magnetic soft actuators can overcome the limited predefined motion of a magnetic actuator into tunable locomotion.[132] Magnetic materials can demonstrate movements beyond simple actuation such as bending or expansion/contraction and closer to complex biomimicry movements. With multiple tapered feet, a soft magnetic millirobot could perform in dry and wet environments at high speeds, strength over 100 times its own weight, and maneuver 90° bending.[133] Inspired by the quick and powerful motions of the biological system for storing elastic energy, a flexible elastomer was connected to a pre-stressed elastomer layer with magnetic NdFeB particles. As the pre-stretch levels increased from 1.2 to 2.9, the blocking force increased from 1.3 N to 4.3 N, together with the strain energy with material. The proposed soft actuator required 5–20 mT to actuate with a response time of 35–40 ms due to the increase in the strain energy by the pre-stretched elastomer layer and allowed quick recovery to its original shape.[134] A liquid–metal-based magnetic soft actuator was fabricated, where magnetic iron particles were embedded inside a Galinstan alloy droplet. The soft actuator existed as a liquid at room temperature, allowing active adaptation to confined spaces and ability to split into multiple portions to reduce its size, whilst undergoing translation motion under magnetic stimuli.[135]

Magnetization patterns can be encoded into magnetic materials, resulting in combined metachronal waves propagating in desired motions.[136] Further variations in magnetization encoding can lead to complex movements such as micro-grippers, jellyfish swimming biomimicry, wire steering, and inchworm movement.[137–142] Altering the domains of nanomagnets resulted in the flapping of a bird and display of various letters from the alphabet.[143]

3D printing technology has also been utilized to program ferromagnetic domains during the printing process of magnetic soft actuators.[144] This minimizes the fabrication time, allows constant output of soft actuators with reliable performances, and applies novel patterning and programming capabilities. Kim *et al.* 3D printed NdFeB/Ecoflex under the magnetization of 2.7 T and achieved a soft actuator that can jump, crawl, roll, transform from a 2D to 3D configuration, and be utilized for drug delivery.[145] A laser heat source coupled with a magnetic field was used for the localized reprogramming of ferromagnetic domains of a soft magnetic actuator. This allowed complex 3D shape morphing of a six-armed and mesh-shaped film under a magnetic field of 150 mT, which could bend different parts of the film in various directions. The individual actuation of distinct magnetic soft actuator arms was showcased to be an electrical switch for light-emitting diodes (LEDs). As different arms of the actuator were deformed, it completed different parts of the LED circuit, lighting some, while others stayed off.[146]

2.5. Pneumatic soft actuators

The most common soft actuators are soft pneumatic actuators (SPAs) due to their innate soft matrix, fast response speed, high force output, low cost, and high strain motion. These properties allow them to be tailorable and easily utilized in a wide range of application fields such as medical devices, grippers, and underwater robotics.[147–149] SPAs are often made from a compliant silicone elastomer matrix with an internal chamber or channel design, achieving deformation with compressed air with positive or negative pressure.[150] Positive-pressure SPAs employ input of compressed air to increase their volume and achieve the desired shape or actuation. Negative-pressure SPAs were employed to achieve contraction motion, which are ideal for limited spaces and not prone to failures from leakage.[151,152] Silicone elastomers are popular soft matrices for SPAs and have a range of moduli and elongation at break. For example, PDMS has a modulus of 1.35–2 MPa with 90% elongation at break, while Ecoflex is more elastic with a modulus of 0.07 MPa and 900% elongation at break.[153]

The actuation of SPAs ranges from simple extension/contraction and bending to more complex shapes such as twisting, locomotion, and surface morphing.[154,155] Single-chamber SPAs rely on the asymmetric thickness of a sample to create a moment arm when the pressurized air forces motion towards the thicker side.[156] The change in geometric parameters or stiffness will also alter the resulting actuation, where extra material or strain-limiting layers have been added to control this actuation.[157] Strategically, stiffening materials can be placed locally to generate larger linear extensions. Sun *et al.* fabricated a customizable SPA using unstretchable fabric, achieving a high blocking force of 2.5 N at 190 kPa.[158] Lee *et al.* 3D printed distinct pin shapes to be utilized in retractable pins. Combined with the layer-by-layer fabrication of an SPA, diverse shapes were pneumatically actuated such as simple bending, "S"-shape, "L"-shape, hook at the end, and even straightening a curved SPA.[75] Gunawardane *et al.* utilized additive manufacturing to fabricate SPAs with spring-like zigzag structures, which could be scaled down under limited space conditions. These designs allowed the SPAs to deform as traditional extension and rotation around their own axis with a blocking force of 10 N under 350 kPa of pressure.[159]

SPAs are typically tethered systems, connected to tubes and pump, which limit their movement. Alternatively, Tolley *et al.* created an untethered robot with all the components (including air compressor) on the SPA. This large SPA of 0.65 m could hold a load of 8 kg, travel at 18 m h^{-1}, and was resilient to being crushed by a car.[160] Multiple deformation modes were achieved by fabricating an SPA with chambers of varying geometries and individual activation. This achieved extension, bending, and twisting motion from the same SPA, allowing it to function as a better gripper compared to simple linear actuators.[161]

Soft lithography and molding are common fabrication processes for SPAs and to create various patterns on elastomers once they are cast and cured.[149] During their fabrication, the unintentional creation of bubbles function as defects in their structure. Zhao *et al.* took advantage of these air bubbles to create details in the sub-millimeter range by degassing at specific locations, which created surface properties for drag-reducing.[162] Although molding is advantageous to create external shapes, it is unsuitable for a design with internal structures such as air chambers. However, the conventional lamination method is prone to rupture and failure at the laminated seams.[163] The retractable pin method allows the elimination of lamination of pieces but is limited to the simple tubular shapes of the pins.[164]

2.6. Photothermal soft actuators

Light-responsive materials can either be constructed by utilizing photochemical or photothermal effects. The photochemical effect relies on application of light at specific wavelengths to "twist" a chemical compound from one isomer configuration to another, which is common in azobenzene-based materials. The consolidation of nano-scale movements within the material results in micro- or macro-scale deformation.[165] The photothermal effect relies on the conversion of light energy into heat as light waves excite electrons into resonant oscillations.[166] This causes a thermal actuation response from asymmetric thermal expansion or *trans–cis* isomerization, similar to the photochemical effect.[167] By adding nanofillers that can convert light into heat, a reversible, fast, and large volume change can be achieved under specific wavelengths.[168] Given that hydrogels can respond to light stimuli and possess inherent softness and flexibility suitable for soft actuators, many photothermal soft actuators are hydrogel-based actuators.

Thermosensitive poly(*N*-isopropylacrylamide) (PNIPAAm) with gold nanoparticles shrunk upon exposure to irradiation from a 532 nm laser (1.1 W cm^{-2}) after 15 min and back to its original state within 5 s.[169] Zhang *et al.* embedded gold nanorods (GNR) coated with polydopamine (PDA) in a liquid crystal elastomer to enhance the photothermal effect from the broadband absorption of PDA. With PDA-coated GNRs, the soft actuator could lift a 0.2 g object to a height of 2 mm in 2 s, while the soft actuator with regular GNRs took twice as long to lift the same object.[170] Wang *et al.* embedded reduced graphene oxide (rGO) sheets in a hydrogel, where an increase in the rGO content and laser intensity enhanced the bending speed and angle due to the change in the solubility of the hydrogel.[171] Compared with the ionic actuators with a long recovery time, this rGO/hydrogel recovered up to 74–84% within 10 s after the removal light of due to the drop in temperature. Subsequently, a double layer made of silver nanowires in a liquid crystal network was doped by azobenzene, which was attached to the graphene oxide layer. The photothermal effect by azobenzene allowed the input near-infrared (NIR) light to be converted into thermal energy, which heated the liquid crystal layer embedded with silver nanowires. The mismatch in the CTE of graphene oxide and liquid crystal layer led to bending deformation.[172] A freestanding film made of 2D MXene nanosheets and a coupling agent, 3-isocyanato-propyltriethoxysilane (IPTS), displayed a reversible bimorph bending actuation similar to the locomotion of an inchworm. This actuation was due to the photothermal effect of MXene, which was further enhanced to a deformation angle of 700° in 2.1 s due to the increased interlayer spacing between the layers and asymmetric microstructure.[173] MXene has also been used as a bilayer with PDMS to fabricate a jumping actuator with controlled jumps by adjusting the incident light angle from 0° to 30° to achieve horizontal to vertical jumps, respectively.[174]

By incorporating a shape memory polymer and carbon black through a 3D printing method fused with deposition modeling, a high photothermal efficiency was achieved for shape recovery under light-stimulation.[175] Liu *et al*. fabricated a liquid crystal elastomer with near-infrared light absorbing cross-linkers. The temperature of the composite could increase from 18 °C to 260 °C in 8 s under light with a wavelength of 808 nm and deform 110% of its original length and hold loads 5600 times its own weight.[176]

2.7. Hydrogel-based soft actuators

Hydrogel-based actuators utilize the exchange of ions from the environment as stimuli to obtain an actuation response. This exchange of ions can be water molecules from the humid environment, hydrogen ions to change pH levels, or other chemical substances in the presence of certain solvents.[38,78,177] These types of stimuli-responsive materials have been studied greatly with many review papers on their use as multifunctional hybrid materials.[68,178,179] Most hydrogels are cross-linked hydrophilic polymer chains with a high-water content (up to 99 wt%), exhibiting more than 10 times strain with high flexible and elastic properties.[180] Although swelling with water is the cause of hydrogel actuation, the swelling/de-swelling process can be initiated by temperature,[181] light,[182] electricity,[183] ionic strength, and more.[184] Hydrogels have high mechanical strength owing to the physical bonding of ionic liquids, and the use of the universally available water as a stimulus enhances their ease of use.[185] Due to their high compliance, the addition of stimuli-responsive nanofillers can generate nanocomposites with a broad range of applications such as drug delivery and soft actuators.[186] However, their dependence on a high-humidity environment, considerable volume exchange loss, and slow speed still require further research and development.

D'Eramo *et al*. photo-patterned over 7800 poly(*N*-isopropyl-acrylamide) (PNIPAM) hydrogel micro-cages with switches that actuated above 32 °C at a speed of 0.6 s.[187] By utilizing hydrogel microspheres in one of the bilayer hydrogel actuator systems, the significant difference in the deswelling rate in the layers resulted in fast bending speeds of 103° per second when actuated at a temperature of 50 °C.[188] Kwon *et al*. fabricated miniature hydrogel-based aquabots utilizing microfluidic chambers. By utilizing different compounds and concentrations, multiple aquabots each responded to different stimuli (*i.e.*, electric, pH, thermal, and magnetic). These robots exhibited locomotive motion for 850 000 continuous actuations.[189] The addition of rGO nanosheets to a hydrogel created a conductive platform to enhance the ion transport within the hydrogel matrix, and therefore faster volume and weight change. A 68% reduction in weight after applying 10 V for 2 min was observed, which was recovered in 6 min after removing the applied voltage.[190] By orienting the dispersed graphene oxide (GO) in a gradient in a PNIPAM hydrogel matrix, Yang *et al*. observed a faster heating rate upon exposure to NIR light on the higher GO concentration side, leading to a greater deswelling rate, rapid response, and large bending of 274° in 45 s.[191] Liu *et al*. fabricated a gradient sodium hyaluronate (HA)/PNIPAM hydrogel soft actuator that could actuate above its low critical solubility temperature (LCST) and recover without additional temperature stimuli due to the different contraction rates of the two materials with maintained elastic behavior of the hydrogel network from the great water retention of HA. They achieved a bending angle of 360° in 15 s in air at 50 °C and recovery to its original shape within 92 s.[192]

3. Multifunctional soft actuators hybrids

As depicted in the previous section, stimuli-responsive polymeric soft actuators have been cultivated into a major field with many advancements in their processing and actuation performance. However, there are still drawbacks impeding the use of soft actuators in real-world applications. For example, SPAs lack blocking force due to their innate soft matrix and are limited to a predefined motion determined by their fabricated air channel, lowering their practicability and adaptability.[193] Magnetic soft actuators require high power and access to an external magnetic field,[39] while piezoelectric actuators only produce small strain. Multifunctional soft actuator hybrids are specifically designed to overcome many of the drawbacks of single-stimuli soft actuators. Often, multiple stimuli materials are integrated, such as magnetic particles into an elastomer with pneumatic channels, mitigating manufacturing complexity with independent activation.[75] In the following sections, we discuss several correlated topics on multifunctional soft actuator hybrids including multiple stimuli-responsive soft actuators for movement with a high degree of freedom, self-sensing soft actuators, self-healing soft actuators, soft actuators with variable structural functions, electrochromic soft actuators, and soft actuators with more than 2 functions (Fig. 4).

3.1. Multiple stimuli-responsive soft actuators for movement with a high degree of freedom

Traditional soft actuators are often bound by their predetermined actuation motion, such as the fixed internal channel design of SPAs. However, by introducing additional stimuli-responsive movements, soft actuators can have a high degree of freedom (DOF) for movement, exhibiting advanced actuation patterns.

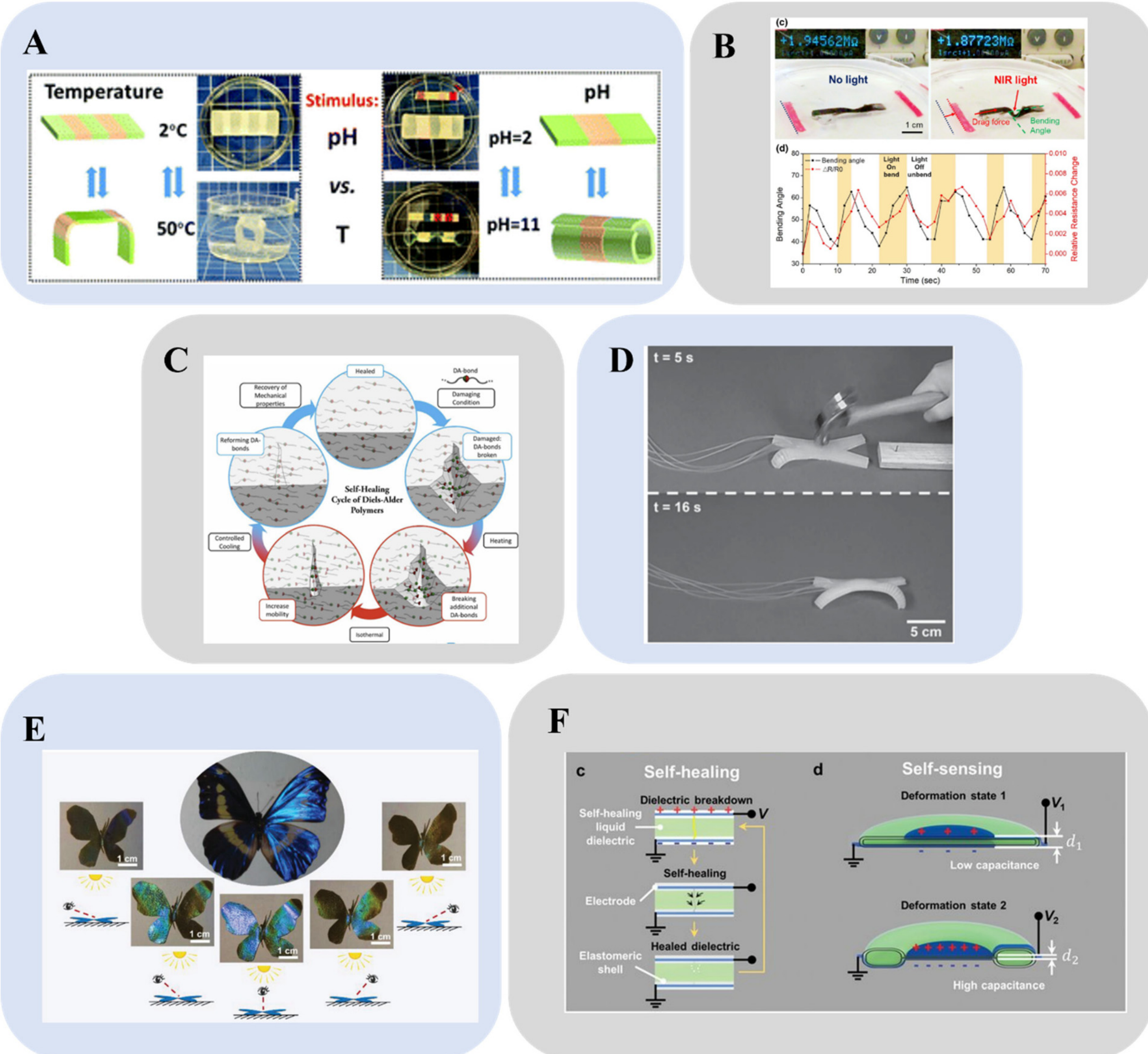

Fig. 4 (A) Multiple stimuli-responsive soft actuator. Hydrogel composite showing temperature- and pH-responsive actuation in bending and rolling motion, respectively. This is achieved through the integration of thermal-responsive and pH-sensitive materials.[194] Reproduced from ref. 194 with permission from the Royal Society of Chemistry, Copyright 2025. (B) Self-sensing soft actuator. Double network of thermo-responsive hydrogel with light-sensitive conductive polymer, resulting in photo and thermal actuation with piezoresistive sensing. The device is shown actuating in water upon NIR light exposure, with the corresponding change in resistance during light-induced bending illustrated in the graph below.[195] Reproduced from ref. 195 with permission from Elsevier, Copyright 2025. (C) Self-healing soft actuator. Diels–Alder (DA) polymer, one of the common healing materials, and its healing mechanism with thermal activation, starting with a mechanical damage that breaks DA and polymer bonds. With the application of thermal stimuli over a period of time, DA bonds are further broken. Subsequently, this reaction allows polymer chains to re-connect and form new crosslinks. Once the DA polymer heals, its mechanical property re-establishes to its original state.[196] Reproduced from ref. 196 with permission from The American Association for the Advancement of Science, Copyright 2025. (D) Soft actuator with variable structural functions. 4-Legged soft pneumatic actuator robot with high toughness achieved by fabricating distinct strain-limiting layers. This soft actuator is more resistant to mechanical damage, such as impacts from a hammer, allowing for longer operational lifetime.[197] Reproduced and adapted from ref. 197 with permission from John Wiley and Sons, Copyright 2025. (E) Electrochromic soft actuator. Bi-directional actuator using humidity and NIR light. The electrochromic effect arises from the self-assembled cellulose nanocrystals on the top layer, refracting light as the wings actuate in a flapping motion.[198] (F) Hydraulically amplified self-healing electrostatic (HASEL) actuator. Owing to its liquid dielectric core in an elastomeric shell, the HASEL actuator can actuate, sense its actuation, and self-heal from dielectric breakdown.[199] Reproduced from ref. 199 with permission from The American Association for the Advancement of Science, Copyright 2025.

Magnetic fillers can be embedded in an elastomer, the same matrix commonly used as soft pneumatic actuators (SPA). Lee *et al*. embedded an Fe_3O_4 magnetic nanofiller into an elastomer with pneumatic channels, creating a magnetic–pneumatic-activated soft actuator. The magnetic actuation added an additional degree of freedom to the SPA, demonstrating dual plane movement to complete an LED circuit. Additionally, the magnetic property was utilized, where a 5-legged star could attract magnetic cargo on water and grab it with pneumatic actuation.[75] A 2D nanoplatelet MXene-based magnetic soft actuator utilized different concentration gradients of $CoFe_2O_4$ nanoparticles to control the absorption and release of water in humid environments. This also allowed the prediction of the bending actuation. Additionally, the soft actuator could undergo magnetic actuation from its magnetic nanoparticles, and photothermal actuation from MXene properties. This allowed the demonstration of various movement patterns such as bending, rotation, and crawling.[200]

Shape memory polymers (SMP) exhibit a shape memory effect by applying temperature to create a secondary shape, alternating between their original and secondary shapes to achieve actuation. An SMP was integrated with SPA, which allowed stiffness control under thermal stimuli. This resulted in multiple degrees of pneumatic deformation from a single air channel.[201] A tri-layer composite of SMP/hydrogel/elastomer composite could undergo actuation through swelling of a hydrogel. Additionally, the shape memory feature allowed 2-way actuation (back to its original shape), as demonstrated by folding/unfolding origami.[202,203] Magnetic Fe_3O_4 nanoparticles at various concentrations were embedded into an SMP, resulting in a high shape memory ratio (recovery to original shaper) of up to 93%.[204] Wei *et al.* printed a magnetic Fe_3O_4/SMP *via* the direct-writing method. The printed sample showed two shape memory effects, deforming into a 3D flower at a water temperature of 80 °C and magnetic actuation recovering its shape at an alternating magnetic field of 30 kHz.[205]

In addition to temperature stimulus, humidity/moisture and photothermal activation can be implemented. A graphene oxide sheet (SGO)/PVDF bilayer actuator was fabricated to activate upon exposure to multiple stimuli. The moisture-triggered actuation from the deformation of its SGO layer resulted in a large bending curvature of 13 cm^{-1} when the relative humidity increased to 86%. Owing to the high negative CTE of the GO layer and positive CTE of PVDF, a large displacement of 42 mm at 140 mm s^{-1} was also observed with changes in temperature and light (photothermal).[206] Dong *et al.* reported that a multi–stimuli-responsive GO/polymer polypyrrole (PPy) bilayer could actuate under humidity, temperature, and light. The multi–stimuli-responsive composite could function as a gripper with changes in relative humidity from 50% to 80% and display forward "crawling" motion due to cyclic light stimuli.[68] By using a hydrogel, ionic and pH responsiveness could be achieved. A "smart" hydrogel bilayer was reported to activate under 3 separate stimuli owing to its thermal- and ionic strength-responsive layer and pH-responsive layer. The hydrogel could change its shape with changes in temperature from 2 °C to 50 °C and pH from 2 to 11.[194] A bilayer of 1D bacterial cellulose and CNT onto a PE film layer could achieve the actuations of photothermal actuation by CNT, electrothermal actuation by the dissimilar CTE of the two layers, swelling actuation due to humidity changes by bacterial cellulose, and reversible de-swelling by PE when exposed to organic solvents. Depending on the stimuli utilized, different motions were observed and a large bending angle of up to 500° with 85 mW cm^{-2} light intensity (36 °C).[207] A bilayer CNT-Nafion/PE soft actuator demonstrated dual directional bending by utilizing thermal actuation in one direction (either by photothermal or electrothermal) and swelling in the other direction (increase in humidity or solvent concentration change). This was due to the dissimilar CTE of the CNT-Nafion and PE layers, and their respective expansion method, where PE will expand under thermal stimuli, while CNT-Nafion does not, and CNT-Nafion layer will expand with hygroscopicity, while PE will cool and shrink due to an increase in moisture in its environment. The bilayer soft actuator reached a bending curvature of 1.12 cm^{-1} and could undergo 100 bending cycles.[208]

Versatility in locomotion can be achieved through adhesion functionality, where soft actuators would not be limited to regular planes but can explore various terrains, even inverted.[209] A DEA was fabricated to achieve multi-functionality in actuation and adhesion, both through electrical stimuli. DEA with electro-adhesive "feet" of copper/polyimide sandwiched layers was constructed to climb walls at a 90° angle, where the adhesion originated from the oppositely polarized "feet" and wall upon the application of a voltage to the "feet". This allowed the DEA to adhere to the wall, and subsequently move upwards through actuation.[210] Hu *et al.* fabricated an inchworm soft DEA with electroadhesion actuators with electrode patterning and voltage signal coordination control strategy. This allowed control of the deformation shape of the main body, while providing enough adhesion to the head and end sections to move at 39.55 mm s^{-1} on an inverted plane. The main body deformation at various pre-stretch ratios achieved up to 16 mm stride length forward at 6 kV of input power.[211]

The electrode arrangement can also be utilized to achieve movement in multiple DOF. Electrical partition of a dielectric elastomer using separated electrodes enabled the creation of individual actuators within the same material, achieving multi-degree-of-freedom to move and bend about two axes.[212] A multi-layer DEA could perform sequential actuation of segments, resulting in an actuator with 3 degrees of freedom that could demonstrate a crawling motion.[213] Conn *et al.* reported a cone DEA with 4 electrode elements to achieve 5 DOF in actuation, with 21.7° and 9.42 mN in rotational actuation and 4.45 mm and 0.55 N in linear actuation.[214]

3.2. Self-sensing soft actuators

Actuators and sensors are complementary, where the sensing component can confirm and verify the deformation and movement executed by the actuator. Actuators with a sensing element are commonly denoted as self-sensing actuators.

Dielectric materials exhibit sensing ability through changes in their capacitance upon a physical change.[215] Taking advantage of its dual functions, a dielectric actuator (DEA) was actuated under 4 kV, whilst performing proprioception sensing through its expansion or contraction.[216] Given that DEAs utilize a high voltage, a material failure monitoring sensor within DEAs to prevent their dielectric breakdown is highly advantageous. Gisby *et al.* reported their initial findings on this topic, where a DEA could sense high-power dissipation before it underwent dielectric breakdown. Thus, in practical applications, a fail-safe mechanism can be integrated when this power dissipation is sensed to prevent the failure and prolong the lifetime use of DEAs.[217]

Verma *et al.* showcased a self-sensing electromagnetic actuator for vibration control of a cantilever beam. The actuation was triggered by a voltage source generating a magnetic field, while the sensor measured eddy currents resulting from the changes in the magnetic flux caused by the displacement of the beam. It was observed that a peak-to-peak displacement of 0.3 mm was dampened to <0.1 mm peak to peak with this device.[218]

Piezoelectric materials are also another type of stimuli-responsive materials that can exhibit sensing and actuation, as either a direct or converse piezoelectric effect. Chen *et al.* used an ionic polymer–metal composite (IPMC)/PVDF bilayer bonded together for actuation based on ion transport and sensing from the direct piezoelectric effect. This bilayer could actuate 0.12 mm with the sensing signal matching that read by a laser sensor.[219] Lee *et al.* utilized functionalized CNT/magnetic nanoparticle/piezoelectric PVDF to apply multiple alignment processing methods that subsequently affect one another.[220] This self-sensing hybrid actuator with piezoelectric sensing and magnetic actuation acted as a vibration damper for transportation vehicles (such as helicopters), successfully lowering the vibration by 0.72 m s^{-2} with 2.5 mV g^{-1} sensing sensitivity.[220] A hybrid magnetic/piezoelectric self-sensing actuator was also 3D printed, achieving a higher weighted damping of 1.8 m s^{-2} and sensing sensitivity of 13 mV g^{-1} due to its scale-up ability.[221] A thin piezoelectric PVDF polymer was also used on a pneumatic bellow soft actuator as a deflection sensor.[222]

Piezoresistive sensing relies on the changes in electrical resistance when deformation occurs. SPAs are commonly integrated with piezoresistive sensors to detect their pneumatic deformation.[223] These sensors are thin and flexible, with some using screen-printing to apply silver strain sensors on an SPA. A 110 mm self-sensing SPA with 90 mm silver sensor actuated curvature up to 21 m^{-1} with a resistance change from 15.8 to 1.7 Ω. This allowed the detection of SPA grippers when opened and closed.[224] Fang *et al.* enhanced traditional SPAs by utilizing liquid to gas phase transition fluid inside an elastomer matrix to achieve both untethered actuation and self-sensing through embedded flexible sensors. The untethered SPA possessed an encapsulated NH_4CO_3 liquid that could undergo a liquid–gas phase transition through the heat generated from NIR light stimulus. This was due to the decomposition of the NH_4CO_3 solution starting at 36 °C. Graphite was placed on the bottom of the SPA, where its resistance would change as the SPA underwent strain. Carbon nanoparticles were placed on the top of the SPA, closer to the external stimuli, whereas the temperature increased, the carbon nanoparticles were less restricted in their matrix and formed better conductive network, resulting in a change in resistance.[225] Yang *et al.* reported an SPA with built-in pressure sensors made of a conductive elastomer, which were co-printed onto the SPA. A prototype gripper was demonstrated for self-sensing actuation when gripping, displaying potential for close-loop control applications.[226] 3D printing can be further utilized to fabricate an SPA with multiple resistive soft sensors. This SPA demonstrated curvature, inflation, and contact sensing with pneumatic actuation, making it ideal for application in the haptics and proprioceptive fields.[227] An SPA was fabricated with thin sheets of polyethylene terephthalate (PET) and metalized PET layers to achieve measurements of its actuated length through changes in the resistance of its metalized PET layer. The measured resistance followed a fit with a cubic polynomial for accurate prediction, allowing a feedback loop to be set up with an average actuated length measurement error of less than 5%.[228]

A self-sensing PNIPAAm/PPy hydrogel composite actuator could shrink upon exposure to photothermal stimuli. This shrinkage with a change in bending angle from 35° to 60° resulted in changes in resistance in the PPy piezoresistive sensor.[195] Relying on photothermal stimuli for actuation, a (polyvinyl alcohol/carbon)/polyethylene bilayer self-sensing film was constructed. The difference in coefficient of thermal expansion between the 2 layers resulted in a large bending deformation of 1260° in 6 s using a xenon light. The carbon layer acted as a piezoresistive sensor, exhibiting a change in resistance by 97% when pressure of 435.5 kPa was applied. The self-sensing actuator was demonstrated as a hand gripper, elephant trunk, and blooming flower.[229]

3.3. Self-healing soft actuators

Given that soft actuators tend to experience mechanical failure, innate self-healing ability will allow reliability and longer operational lifetime. Self-healing ability arises from either embedded chemical reactions that occur at failure or molecular healing ability from the material itself, and can also be controlled by external stimuli, such as temperature. Biologically inspired, self-healing function will add onto their future potential as artificial muscles or other actuator systems that need minimal maintenance.[230]

Pena-Francesch *et al.* fabricated an SPA with a self-healing protein membrane at the perimeter, which could crosslink the broken polymer chains through temperature changes. After healing, the SPA could maintain the same maximum actuation strain of 400% and 5 N blocking force, displaying successful recovery in mechanical property and performance ability.[65] To overcome the dielectric breakdown challenges in DEAs, a two-phase material consisting of a dielectric elastomer and silicone sponge foam containing silicone oil was utilized for self-healing ability. When punctures were made on the two-phase DEA, the silicone oil would flow into the void defect to restore its dielectric integrity, maintaining its performance over 2000 cycles of actuation and 6 rounds of punctures.[231]

Terryn *et al.* fabricated an SPA with a Diels–Alder polymer to allow the self-healing of macroscopic cuts of 8–9.5 mm under thermal stimulus of 80 °C. Although there was a decrease in modulus after each healing cycle due to the formation of irreversible bonds, this decrease was minimal, resulting in a modulus recovery efficiency of 93.4%.[232] Utilizing the Diels–Alder polymer, greater interfacial strength was observed at the healing location after healing at 85 °C or higher due to the formation of covalent bonds. This resulted in a new fracture occurring at the bulk of the material rather than at the previously healed location.[232] Cao *et al*. reported the fabrication of a hydrogel actuator that actuates with changes in relative humidity (20% to 90%), whilst having self-healing ability from its reversible hydrogen bonding cross-linking networks.[233] Photothermal stimulus was utilized for both the actuation and self-healing response of a poly(ethylene-*co*-vinyl acetate) nanocomposite with embedded silver nanowires, which assisted in the temperature changes of the semicrystalline polymer.[234] The actuator deformed to various geometries such as "I" and "U" shapes under either air or water environments when the temperature was above 78 °C. It also exhibited self-healing ability under photothermal stimulus due to the re-crosslinking of its polymer chains, healing itself after it was cut into 2 parts. Highly ordered metal nanostructures were used to fabricate anisotropic hydrogels that could undergo self-healing when exposed to an NIR laser and low pH environment due to the interactions between thiolate and silver elements. The hydrogel nanocomposite demonstrated in-plane and out-of-plane bending when exposed to specific solvents, which was dependent on the lamellae direction (perpendicular or parallel to the surface).[235]

Interestingly, the electrode design has also been utilized to prolong the operational life of soft actuators by either preventing or overcoming failures. Ren *et al*. utilized PEDOT conductive polymer as an electrode for the piezoelectric polymer P(VDF-TrFE-CFE). The self-healing ability of PEDOT isolated locations with electrical breakdowns to support continuous piezoelectric actuation. The piezoelectric composite had high strain of over 5% and electric energy density of 0.5 J cm^{-3}.[236] Michel *et al*. fabricated a DEA with reduced graphite in silicone as a self-healing electrode. After dielectric breakdown at 2200 V and 10 Hz for 100 cycles, the electrode could heal itself through possible silicone oxidation, creating inactive sites that were not part of the conductive electrode path. The DEA could continue to function after 14 cycles to its original lateral strain of up to 3.6%.[237] This technology can be utilized to enhance the reliability of actuator/electrode systems, reducing failures due to electrodes.

3.4. Soft actuators with variable structural functions

Previous sections focused on soft actuator hybrids with non-structural functions, such as sensing and healing. Multifunctional actuators can also be utilized for improving structural functions, such as stiffness and fatigue. This enhancement in the mechanical properties of soft actuators allows their reliable operation in real-world conditions.

Altering the stiffness of a soft actuator allows a larger bending motion at a lower power input. Huang *et al*. embedded magnetic particles into a thermal-stimuli responsive material to control the morphology of the folding/unfolding actuation through magnetic field-induced stiffness.[238] SPA grippers with the integration of an SMP allowed varied stiffness by changing its modulus around its glass transition temperature. The stiffness ratio was found to be 24.9 times from room temperature to 60 °C, allowing the SPA to easily bend when heated above the glass transition temperature.[202] In a tri-layer shape memory polymer/hydrogel/elastomer composite, the SMP was utilized to stiffen the composite, withstanding a 50 g load.[203] An SPA with strain-limiting layers (PDMS, paper, and Nylon) was constructed to achieve pneumatic actuation with increased resistance to various stress (tensile, compression, impact, *etc*.) and increased toughness. The SPA composites could withstand stress in the range of 8.25 MPa to 10.2 MPa, with no loss of function, a value that would normally render SPAs irreversibly damaged.[197] Moreno-Mateos *et al*. utilized a combination of soft and hard magnetic particles (carbonyl iron powder/NdFeB/PDMS) to demonstrate torsional actuation and changes in stiffness. It was found that the interaction of soft and hard magnetic particles amplified the magnetization from an applied magnetic field and could achieve a 150% larger stiffening effect compared to the composite with solely hard magnetic particles.[239] Alginate was used as a rheological modifier on various hydrogel materials through direct ink writing. The printed pneumatic actuators exhibited enhanced mechanical toughness with bending and rotation movements.[240] Lalegani Dezaki *et al*. integrated strontium ferrite magnetic microparticles into SMP foam to achieve controlled gripping ability. The SMP foam allowed greater contact during gripping motion, allowing heavier objects to be lifted, as well as horizontal gripping due to the stability provided by the SMP foam.[241]

3.5. Electrochromic soft actuators

Electrochromism is a reversible color change or transmittance in a material due to electrically driven ion movement. These materials have been studied extensively for their use in wearables, portable electronics, smart windows to mitigate energy loss, and next-generation displays.[242] An electrochromic DEA was fabricated by applying a gold coating onto a DEA, achieving a soft actuator that could transition from transparent to opaque states with an applied voltage. This change was possible because the applied voltage deformed the gold coating into wrinkles, reflecting and refracting light in such a way that the DEA appeared transparent when the gold coating was flat and translucent when the gold coating was wrinkled.[243] Inspired by the stretchable skin of the octopus, which can undergo color changes for disguise, an actuator was fabricated with proprioception through illumination. The layered SPA composite was comprised of a hydrogel as its matrix with 3 chambers and an elastomer with doped ZnS phosphor for electroluminescence, emitting light under an electric field due to electron excitation. When each chamber was actuated with pneumatic pressure, the capacitance changed up to 1000% as its thickness decreased, ensuing the illumination of this chamber. This type of optical proprioception allowed users to visually identify the deformation state of the soft actuator.[244] Li *et al.* fabricated a bilayer of cellulose nanocrystals (CNC)/silver nanoparticles (AgNPs) dispersed in polyurethane (PU) to undergo dual direction deformation, which changed color due to the Bragg scattering of light from the twisting rod morphology of CNC. The color change from brown to blue could be observed by the naked eye as the bilayer bends one direction from NIR light and another direction from an increase in moisture.[198]

3.6. Soft actuators with more than two functions

Given that soft actuators can be used for a diverse range of applications, their requirements and optimization parameters will also differ. In this section, we present an overview of many multifunctional soft actuators that can perform more than two functions.

A soft actuator composed of a solid-state poly(ionic liquid) filler in a DEA and PDMS/ZnS/Cu allowed fast healing properties due to the ionic interactions of the poly(ionic liquid) filler and light emission from the PDMS/ZnS/Cu material. The fabricated DEA had a healing efficiency of 65% over five cycles of self-healing, visual light emission with the application of a voltage, and a bending angle of 44.7° upon the application of 12.6 V μm^{-1}.[245]

Hydraulically amplified self-healing electrostatic (HASEL) actuators are polymer shells filled with a liquid dielectric, combining DEAs and fluidic actuators.[246] HASEL actuators can perform 3 different functions of actuation, sensing, and self-healing. Similar to dielectric actuators, the application of a voltage will result in electrostatic forces between the electrode locations. However, given that the DEA is in liquid form, hydraulic pressure is generated outside the electrode area, which results in force output. Additionally, with an applied electric field, the deformation can be measured by capacitance sensing from dielectric materials.[247] The self-healing ability emerges from the use of a liquid dielectric, which returns to an insulating state after dielectric breakdown. An HASEL actuator could undergo 50 dielectric breakdowns without permanent damage. This self-healing ability allowed the scaling up of HASEL actuators to achieve a larger actuation magnitude of 7 mm with capacitance peaks matching deformation.[199] Building on HASEL actuators already possessing self-sensing and self-healing abilities, copper-doped zinc sulfide particles were utilized for an additional electroluminescent property. As the HASEL actuator deformed and the distance between the electrode increased or decreased, the emission rate of the dopant ions differed and various luminous intensities were emitted, resulting in a visual sensing component. With a strain of 25%, an electroluminescent intensity of 23 cd m^{-2} and definitive light emission were achieved.[248]

Controlled hydrophobicity can be used for the fabrication of self-cleaning soft actuators. By changing their topology and surface area, super hydrophobicity can be triggered to remove biofouling from the surfaces of elastomers.[249] The fabrication of a soft actuator with functionality in transmittance and hydrophobicity was reported using crumpled graphene and DEA. Due to the deformation caused by an applied electric field, the crumpled graphene exhibited novel properties such as transmittance of 40–60%. Crumpled graphene was also observed to have tunable wettability, exhibiting hydrophobicity with a contact angle of 152°.[250]

4. Applications

Multifunctional soft actuators can be used for numerous applications, which is rapidly increasing. With continuing developments, they have been demonstrated in the automotive and industrial fields as intake manifolds, MEMS, artificial muscles, actuator textiles and many more.[179] Additionally, research has been focused on using these multi-functional soft actuators in the medical field as rehabilitation or robotics, haptics, and terrain exploration for rescue missions (Fig. 5).

4.1. Biomedical

Soft actuators are especially useful for biomedical applications, where the soft bodied nature of animals/humans cannot be achieved by their conventional stiff mechanical counterparts. This includes human-assisted devices, artificial muscles, and *in vivo* medical and assistance in surgery.[255]

SPAs have great potential for at-home rehabilitation applications due to the high deformation and force from their pneumatic deformation combined with their proprioception and/or pressure sensing ability. The repetitive hand functions performed by soft actuator gloves will increase the strength, accuracy, and range of motion of the hands, making them ideal for people with injuries that prevent them from performing basic daily activities such as holding an object.[155,256] Kim *et al.* went a step further and integrated soft rehabilitation gloves with a learning-based intention detection method for the program to detect the intentions of the user through visual information to grab certain objects.[257] This type of development advances the at-home rehabilitation of soft actuators, allowing individuals with disabilities to achieve a level of normalcy. Rehabilitation of larger limbs, such as the forearm, can be applied using a novel embedded core casting technique to reinforce higher input air pressures to create high output force.[163] At a full-bodied scale, a soft exoskeleton driven by fluidic pressure was fabricated to assist leg and back rehabilitation for walking.[258]

Artificial muscles are soft actuators that can mimic natural muscles through their properties and performance. In this field, soft actuators are most commonly demonstrated by grippers with bending-, twisting-, and elongation-type movements.[132] As the gripper motion evolves, the types of objects it can grip also become more elaborate. For example, a simple bending motion SPA soft gripper can grab large hard objects or rectangular or circular shape.[163,196,232] Alternatively, an SPA with twisting motion with multiple sections can grasp lightweight flowers, the narrow neck of a wrench, or complex shapes such as a horseshoe.[259] Focusing on hand dexterity,

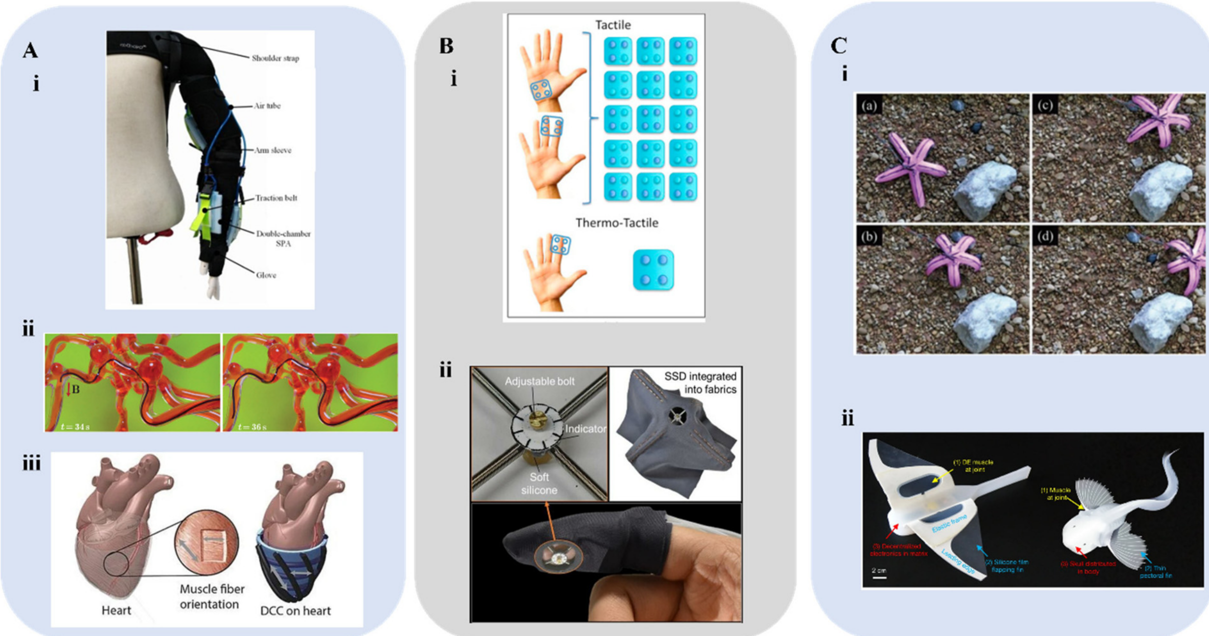

Fig. 5 (A) Biomedical applications. (i) Two-part soft pneumatic actuator with fiber-reinforced and elastic materials to manufacture a high force soft wearable actuator. Owing to the high load this device can withstand, it can be used to assist in the bending of a large limb such as the forearm.[163] Reproduced from ref. 163 with permission from Elsevier, Copyright 2025. (ii) Demonstration of ferromagnetic soft robot used for surgical application in a cerebrovascular network. The two panels show the use of a magnetic field (B) to direct the soft robot downwards in 2 seconds through the phantom vessel.[76] Reproduced from ref. 76 with permission from The American Association for the Advancement of Science, Copyright 2025. (iii) Schematic of soft sleeve for assistance in human heart function. The design is inspired from horizontal and angled vertical muscle fiber orientations, resulting in a sleeve with compress/decompress (positioned horizontally) and twist/untwist (positioned angled vertically) deformation capabilities, as shown by the grey arrows.[251] Reproduced and adapted from ref. 251 with permission from The American Association for the Advancement of Science, Copyright 2025. (B) Haptics applications. (i) Illustration of a 2 × 2 tactile display system for pattern recognition task. The stimulation to the fingers and palm is applied through force and temperature, enhancing the identification by the user.[252] Reproduced from ref. 252 with permission from Elsevier, Copyright 2025. (ii) Wearable tactile device for fingertips with 3-axis stimulation capability. The skin stretch device (SSD) is woven into the fabric and will interact with the fingertip by stretching the skin in 3 directions using shear force.[253] (C) Applications for rescue and mobility. (i) Soft starfish-like actuator demonstrating high robustness to its environment, such as a rocky terrain. The soft actuator navigates through this terrain with multiple gait patterns of various relaxed and contracting legs to safely roll down a large rock.[254] Reproduced and adapted from ref. 254 with permission from Springer Nature, Copyright 2025. (ii) Design of a dielectric soft robot inspired from the characteristics of a snailfish (right). The elastic frame and film produce a flapping motion with the application of a voltage from an attached battery. The device could swim underwater in various bodies of water such as the Mariana Trench and the South China Sea.[58] Reproduced from ref. 58 with permission from Springer Nature, Copyright 2025.

small objects such as a pen lid can be held using the pincer grasp demonstrated with the thumb and the index finger. This can be expanded to holding a pair of scissors or chopsticks, successfully mimicking the operation of human hands.[260] Mimicking the ability of human hands, light-triggered soft actuator hands demonstrate counting finger movements[171] and SPA fingers can play music on a piano.[261] By attaching a vacuum suction cup to the soft robotic grippers, objects could be picked up and relocated without gripping traction challenges.[152] Zhu *et al*. coupled soft and ridged actuators in parallel, where the selective actuation of each actuator resulted in multiple actuation modes, allowing the grasping performance of unique objects such as 0.1 g potato chips or objects that offset from the center.[262] To accurately mimic the motion and effectiveness of human finger joints, Yang *et al*. optimized the finger design with a buckling joint. By creating a V-shaped opening along the plane with a high stress concentration, the central and side membranes are separated. When the finger is deformed in a bending motion, the side membranes buckle outward, while the central membrane buckles inwards in a fast "snap-through" motion. This design demonstrated a large bending angle of 100° at 0.24 s and could hold at least 5.8 kg.[263] Although many of these soft actuator grippers have the appearance of a human hand, object manipulation does not necessarily need this presentation. An electroactive hydrogel with thin beam arrays (also denoted as "hairs") could manipulate an object between these arrays, transporting a hoop back and forth.[183]

In vivo medical applications, such as robotic drug delivery, body exploration, organ assistance, and smart lenses, have been designed to enhance the quality of human life. Hydrogel "bio-bots" were 3D printed with a skeletal muscle strip and electrically activated to move at 156 μm s^{-1}, corresponding to covering a full human body length per minute. The "bio-bots" were designed to move about inside a human body for potential drug delivery, tissue engineering, and biomimetic machine design.[264] Biohybrid films using engineered tissues and polymers could also be utilized for human body exploration, exhibiting the high specific force of 4 mN mm^{-2}.[265] Soft actuators have also been studied to act as artificial organs, presented as an implantable soft sleeve around the heart to assist in heart function.[251] Lastly, DEAs can be utilized for optical lens applications. Upon electrical activation, the DEA would deform and alter the focal length required by optical lenses. Although this method has great potential for future optical lens applications with advantages such as small size, lightness, and silent operation, the voltage applied is still too high for use.[266] Jung *et al.* used a soft fluidic actuator to achieve reversible deformation into a hemispherical shape, which allowed the camera lens to focus immediately with an adjustable zoom capability of 3.5 magnification.[267]

Soft actuators also have great potential to be utilized as surgery robots, where minimally invasive surgery requires tools to navigate between organs and tissue without harming their path.[268] Using a three-chamber fluidic elastomer actuator, the mobility of the surgical tool was controlled by a single fluid supply with multiple wirelessly controlled valves.[269] Lu *et al.* reported that an electroactive soft actuator could be turned into an active catheter with multiple degrees of freedom bending ability at a low voltage of 1 V. This soft actuator could bend at the micrometer and millimeter scales, making it an ideal surgical tool for manipulation in the human body.[270]

4.2. Haptics

As the world advances and evolves to bring technology into our everyday lives, the field of haptics is critical. The sense of touch that haptics brings to the user can be used in a variety of fields, such as virtual reality (VR), where the tactile feedback from multifunctional soft actuators can enhance the realism of VR.[271,272] Electromagnetic–pneumatic actuation was utilized as 2 × 2 tactile cells to relay information to the fingertips of the user.[252] These devices could apply both mechanical and thermal stimuli to the skin, improving the imitation and identification of everyday objects in the virtual world. Out-of-plane and in-plane mechanical stimulation on the human skin utilized the shear movement of soft actuators, where test subjects could distinguish different directional stimuli with 80% accuracy with a 5 × 5 array.[273] Employing a wearable tactile glove, 3-dimensional tactile sensation was applied as a skin stretching feeling.[253] By integrating an electrostatic actuator with a DEA, the haptics device could enhance its displacement and blocking force by 19% and 26%, respectively, compared to the DEA alone.[274] Haptics can also be applied to assist those with disabilities, such as a refreshable braille board for people with impaired or low vision, creating varying braille patterns raised from an initially flat board.[275]

4.3. Rescue and mobility

Inspired by earthworms, soft actuators can also be used in applications analogous to natural disaster response and rescue efforts. Multifunctional soft actuator hybrid worms could enhance rescue efforts after earthquakes, as researched by locomotion motion.[276] A starfish-shaped soft actuator with a shape memory effect was assessed on various terrains (sand, rough ground, and rocks) and its crawling motion was observed with speed ranging from 20.7 mm min^{-1} in rough terrain to 130 mm min^{-1} in dry terrain. It demonstrated the ability to climb over rocks twice its height (12.2 mm) and displayed rolling motion to clear rocky terrains.[254] GoQBot is a robot design to mimic the rolling of caterpillars, exhibiting 1 G of acceleration at 200 rpm of angular velocity.[277] This speed can aid in reaching victims after natural disasters for preliminary triage. Multifunctional soft actuator hybrids for underwater exploration have also been designed, where they were tested in the Mariana Trench to a depth of 10.9 km as untethered systems.[58] Underwater environments were also explored. Soft robotic fish for untethered underwater motion was achieved by controlling localized buoyancy for forward ascension and descension. This was achieved through thermoelectric pneumatic actuators, where the heating and cooling induced a rapid fluid phase change to expand and collapse the pneumatic actuators.[278]

5. Challenges and future prospects

The field of multifunctional soft actuator hybrids and their immense potential were discussed in-depth herein. According to the considerable research in the medical field (human-assisted devices and artificial muscle), VR, and their capabilities for terrain exploration, soft actuator hybrids are proving to be attractive technology. As this field develops, many more potential applications are sure to emerge. Multifunctional soft actuator hybrids are often specifically fabricated to overcome the common disadvantages of soft actuators, such as low lifetime, long response speed, and requirement of a power source.[179] However, these hybrids still have many major challenges as researchers evaluate their processing and performance before they can meet operation standards.

One major challenge associated with multifunctional soft actuator hybrids is their scalability issue. The processing of these soft polymeric materials is currently taking place on a research scale. Although some large soft actuators have been produced on the scale of meters, only one device is usually fabricated.[279,280] Scalability especially becomes an issue when specialized polymers and/or nanofillers are utilized to obtain multi-faceted properties, resulting in costly scale-up ventures. Additive manufacturing, or 3D printing, of soft actuators has been utilized for ease of processing and increased reproducibility. However, custom materials are often not recommended by commercial 3D printer manufacturers and provide standard single polymeric materials. These printers are also limited by their print bed size and their slow printing speed hinders large-scale manufacturing.[281,282] If this challenge can be solved, 3D printing can be utilized for the mass production of devices at a lower cost, allowing greater accessibility.

The resulting small size of soft actuators leads to another challenge, low blocking force. The combination of the small size of soft actuators and its innate soft nature leads to low force when actuated. Although this may be beneficial for some applications, such as the delicate touches of haptics, it can be detrimental to the majority of applications that involve the manipulation of heavy objects.[283,284] These applications include those already employing mechanical actuators, such as automotive applications, and new potential applications such as implantable soft sleeves to apply enough force to enable heart function.[251] Thus, to overcome this issue with limited blocking force, some researchers employ large supports and power supplies (*i.e.*, pneumatic pumps), which exceedingly increase the size of the system, leading to complex application practicality.[7,258]

Lastly, multifunctional soft actuators have a material and system integration issue, which arises due to the novelty of this field. Numerous traditional stimuli-responsive soft actuators have been researched for decades but the combination of multiple properties and functionalities is not as simple as their straightforward addition. When various materials are combined, their unique interactions will result in new properties and may even hinder functionalities that were originally part of the individual materials. Identifying materials that are complementary and enhancing the desired functionalities without inhibiting others require fundamental knowledge into each material and system separately. By recognizing how functionalities are produced and the lone architecture of the material, new integration can begin and successfully achieved. In terms of system integration, many research works have demonstrated the performance of their multifunctional soft actuator hybrids, but in an open-loop control with no active feedback.[220,253] As many systems require constant feedback during operation to correct or validate their performance, such as the field of haptics, closed-loop designs are necessary for integration.

6. Conclusion

The field of soft actuators is intriguing, which sets itself apart from other fields due to its "soft" aspect. Traditional stimuli-responsive soft actuators have been well-studied, but their bound stimulus and exclusive actuation function limits their practicality, hindering their ability to reach their full potential. Multifunctional polymeric soft actuator hybrids exhibit multi-stimuli-responsiveness with various functions, offering complex manipulation with unbounded movements and potential as stand-alone fully operational systems. This review focused on the essential and novel field of soft actuators given that its ongoing development is promising for success in real-world applications. Firstly, the development of traditional stimuli-based soft actuators was illustrated, leading to the diverse creation of multifunctional soft actuators. These include material integration design for high actuation freedom, self-sensing, self-healing, varying structural functions, and many others. Although many challenges still remain, the future of multifunctional soft actuator hybrids is full of potential, ranging from their recent application in the biomedical field and haptics to rescue devices. With tailored optimization and development considering a specific application, multifunctional soft actuator hybrids will be better equipped as solutions to issues encountered globally.

Data availability

No primary research results, software or code have been included, and no new data were generated or analyzed as part of this review.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors acknowledge the funding support from different agencies for this research, including Natural Sciences and Engineering Research Council (NSERC) of Canada, and the National Research Council Canada (NRC).

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